

# Interannual and seasonal variations in energy and carbon exchanges over the larch forests on the permafrost in northeastern Mongolia

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## Abstract

The larch forests on the permafrost in northeastern Mongolia are located at the southern limit of the Siberian taiga forest, which is one of the key regions for evaluating climate change effects and responses of the forest to climate change. We conducted long-term monitoring of seasonal and interannual variations in hydrometeorological elements, energy, and carbon exchange in a larch forest (48°15'24"N, 106°51'3"E, altitude: 1338 m) in northeastern Mongolia from 2010 to 2012. The annual air temperature and precipitation ranged from −0.13 °C to −1.2 °C and from 230 mm to 317 mm. The permafrost was found at a depth of 3 m. The dominant component of the energy budget was the sensible heat flux ( $H$ ) from October to May ( $H/\text{available energy } [R_a] = 0.46$ ; latent heat flux  $[\text{LE}]/R_a = 0.15$ ), while it was the LE from June to September ( $H/R_a = 0.28$ ,  $\text{LE}/R_a = 0.52$ ). The annual net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (RE) were −131 to −257 gC m<sup>−2</sup> y<sup>−1</sup>, 681–703 gC m<sup>−2</sup> y<sup>−1</sup>, and 423–571 gC m<sup>−2</sup> y<sup>−1</sup>, respectively. There was a remarkable response of LE and NEE to both vapor pressure deficit and surface soil water content.

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**Keywords:** Energy and carbon flux; Larch; Permafrost; Mongolia; Vapor pressure deficit; Soil water content

## 1. Introduction

The concentration of atmospheric CO<sub>2</sub> has increased from a pre-industrial value of about 280–379 ppm in 2005 (Solomon et al., 2007). Forests

cover 30% of the land surface and store 45% of terrestrial carbon, and can sequester large amounts of carbon annually (Bonan, 2008). Luysaert et al. (2007) have made a comprehensive analysis of the carbon budget using data from 513 forest sites from all over the world. They showed that the gross primary production (GPP) of forests, which is the gross uptake of CO<sub>2</sub> that is used for photosynthesis, benefited from higher temperatures and precipitation. On the other hand, the net ecosystem production (NEP), which is

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the balance of net primary production (NPP), that is, the balance of photosynthesis and autotrophic respiration and heterotrophic respiration, was found to be independent of annual temperatures and precipitation (Luyssaert et al., 2007). They suggested that the carbon budgets of semiarid forests (boreal, temperate, and tropical) would benefit most from additional data inputs due to small sample sizes and high variability among sampled sites. Boreal forests had a consistent average sink of  $0.5 \pm 0.1 \text{ PgC y}^{-1}$  for 1990–2007 and Asian Russia had the largest carbon sink in boreal forests (Pan et al., 2011). Schulze et al. (1999) argued that European forests have a higher total net primary productivity than Siberia ( $1.2\text{--}1.6$  vs.  $0.6\text{--}0.9 \times 10^{15} \text{ gC per region per year}$ ), despite a smaller area, because of differences in growing season length, climate, and nutrition. In East Asian forests, there is a clear linear relationship between annual GPP and annual mean air temperature (Hirata et al., 2008). Hirata et al. (2008) also found a strong exponential relationship between annual ecosystem respiration (RE) and annual mean air temperature. In their analysis, the photosynthetic photon flux density influenced the seasonal and interannual variation of GPP of subarctic and temperate forests while GPP was not influenced at the other sites. Kato and Tang (2008) estimated that the net ecosystem exchange (NEE: negative NEE indicates sequestration of carbon from the atmosphere into the terrestrial ecosystem) at forests in boreal Asia was  $-132.6 \pm 73.7 \text{ gC m}^{-2} \text{ y}^{-1}$ , which correlated linearly with mean annual temperature and logarithmically with precipitation. They suggested that additional information should be obtained in the future from arid areas of Asia to evaluate the effect of drought on the NEE. In addition, they pointed out that the shorter period of measurement may cause significant bias in some ecosystems due to the failure to account for the effect of disturbances. There have been limited studies regarding the long-term carbon budget of subarctic forests.

Surface climate is determined by the balance of fluxes, which can be changed by radiative (e.g., albedo) or non-radiative (e.g., water-cycle-related processes) terms. Both radiative and non-radiative terms are controlled by details of vegetation (Denman et al., 2007). The atmosphere both controls and responds to the partitioning of solar energy into sensible and latent heat (evaporation) fluxes at vegetated surfaces, largely because of stomatal regulation. Evaporation is also a major component in the water balance, influencing water availability and so on, and influences ecosystem dynamics including carbon sequestration and storage

(Kelliher et al., 1997). Forests have low surface albedo and can mask the high albedo of snow, which contributes to planetary warming through increased solar heating of the land. The ratio of evapotranspiration to available energy is generally low in forests compared with some crops and lower in conifer forests than deciduous broadleaf forests (Bonan, 2008). The boreal forest, one of the world's larger biomes, is distinct from other biomes because it experiences a short growing season and extremely cold winter temperatures (Baldocchi et al., 2000). In boreal forests in Canada, the evapotranspiration rate was less than  $2 \text{ mm d}^{-1}$  over the growing season for coniferous species according to the observations of the Boreal Ecosystem Atmospheric Study (BOREAS; Sellers et al., 1995). The coniferous sites of BOREAS were observed to have the lowest growing season albedos for any vegetated surface that we know of, about 0.08, and the winter albedo was around 0.25 (Sellers et al., 1997). Despite the potential importance of the Siberian taiga in the Asian boreal region's surface-atmosphere energy exchange for regulating the Northern Hemisphere climate, there was little study of surface fluxes in this region (Kelliher et al., 1997). They showed that the average daily evaporation was  $1.9 \text{ mm d}^{-1}$  in a 130-year-old stand of larch trees (*Larix gmelinii*) located 160 km south of Yakutsk in eastern Siberia, which is relatively low. Although their observation was for only 2 weeks in July, the mean evapotranspiration rate was  $1.16 \text{ mm d}^{-1}$  from April 21 to September 7, 1998, while it was  $1.5 \text{ mm d}^{-1}$  for the growing season from June 1 to August 31 in a larch forest near Yakutsk in eastern Siberia (Ohta et al., 2001). Ohta et al. (2008) found that the annual evapotranspiration, including interception loss, was relatively steady at  $169\text{--}220 \text{ mm y}^{-1}$  compared with the wide range in annual precipitation ( $111\text{--}347 \text{ mm y}^{-1}$ ) for 7 years from 1998 to 2006 in a larch forest in eastern Siberia at the same site as Ohta et al. (2001). Dolman et al. (2004) revealed that the average evapotranspiration rate of the forest approached  $1.46 \text{ mm y}^{-1}$  during the growing season, with peak values of  $3 \text{ mm y}^{-1}$ . Most studies were based on a single year of measurement except for Ohta et al. (2008). They pointed out that the interannual variation of evapotranspiration was small, but the yearly evapotranspiration coefficient (the ratio of evapotranspiration to potential evaporation) ranged from 0.30 to 0.45, which suggests that the interannual variation of evapotranspiration was controlled by the regulation of the land surface rather than by atmospheric demand. They also suggested that the soil

moisture content was the most important variable among the factors determining the evapotranspiration coefficient at an interannual temporal scale.

Sugimoto et al. (2002) showed that larch trees used rainwater during a wet summer, but meltwater from permafrost was used during a drought summer according to their analysis of the stable oxygen isotopes (a useful tracer to determine the origin of water) from plant water (sap water), soil water, and summer precipitation in east Siberia. Soil water stored in the upper part of the active layer (from the surface to about 120 cm) can be a water source for transpiration in the following summer while the soil water stored in the lower part of the active layer would not be used by plants in the following summer (Sugimoto et al., 2003). The foliar oxygen isotopic composition indicated that during most of the growing season, larch trees took water from the upper 30-cm soil layer, and the deeper layer when the water supply at the upper soil layer was limited (Li et al., 2006). In July and August, larch trees in the forests of Mongolia tended to shift their water uptake to shallow depths in response to recent rainfall, but during June and September, the depth of water uptake was unclear based on stable water isotope analysis (Li et al., 2007a). As they did not sample the soil water from deeper layers, there were still unknown processes of water uptake by larch trees. Regarding the water use efficiency of larch in Mongolia, Li et al. (2007b) showed that the Mongolian larch forest exhibits a higher water use efficiency than that by the other larch forests with a strong seasonal variability based on the carbon isotopic composition of the plant tissue as a surrogate for evaluating plant water use efficiency, which is likely to be an adaptive strategy for growth and survival of the larch trees in this cold semi-arid environment.

As climate change by global warming continues, the ecosystem at ecotones (boundaries between two kinds of biomes) might be affected. The southern limit of the Siberian taiga forest and permafrost are located in Mongolia, where there is an ecotone between forest and steppe. The closed forests occupy 12.7 million ha, 8.1% of the land area of Mongolia, and are dominated by larch (*Larix sibirica*) forests, which comprise 75% of the forested area (Tsogtbaatar, 2004; Ykhanbai, 2010). In northeastern Mongolia, permafrost was found beneath north-facing forested slopes and flat pasture plains where it is overlain by a wet active layer, while permafrost was absent beneath south-facing pasture slopes characterized by a dry active layer (Ishikawa et al., 2005). Disturbances in the forest such as fire, logging, and pest outbreaks have negative

impacts for the forests (Tsogtbaatar, 2004; Ykhanbai, 2010). Climate change has caused remarkable increases in air temperature (1.8 °C in the past 60 years) and changes in precipitation (7.5% decrease in summer and 9% increase in winter) in Mongolia (Batima et al., 2005). These climate changes and human impacts (e.g., logging and grazing) might affect the ecosystem of Mongolia, especially for forest distribution. Since declines of productivity and regeneration are more widespread in the Mongolian taiga than the opposite trend, a net loss of forests is likely to occur in the future, as strong increases in temperature and regionally differing changes in precipitation are predicted for the twenty-first century (Dulamsuren et al., 2010). Drought is a key factor explaining the forest–steppe borderline in northern Mongolia and may decrease with increasing aridity due to global warming (Dulamsuren et al., 2008). Tree-ring widths increase with decreasing summer temperatures, increasing precipitation during the growing season, and decreasing winter precipitation (Dulamsuren et al., 2011).

To clarify the climate change effect on forest growth, a better understanding of the hydrometeorological and carbon cycle processes is required. Therefore, we need more long-term monitoring data in larch forests of Mongolia. However, the energy and carbon budget studies of larch forests of Mongolia are limited. The annual cumulative NEE was  $-120$  to  $-150 \text{ gC m}^{-2} \text{ y}^{-1}$  from 2003 to 2005, indicating that the forest acted as a net sink of  $\text{CO}_2$  over a montane larch (*L. sibirica*) forest in Mongolia (Li et al., 2005; Hirata et al., 2008). Since one of these studies was of a single year (Li et al., 2005), while the other was a multiyear study, but only using mean annual values (Hirata et al., 2008), the multi-year seasonal variation of energy and carbon fluxes of Mongolian larch forests is still unknown. These studies also did not show the energy budget and its relationship with the carbon budget.

This study aims to investigate the interannual (2010–2012) and seasonal variation of the energy and carbon budgets to clarify the effect of climate variability on the energy and carbon exchanges over the larch forest on the permafrost in northeastern Mongolia.

## 2. Material and methods

### 2.1. Observation site

Long-term monitoring of the energy and carbon balances and hydrometeorological elements and

phenological camera monitoring have been carried out at the Udleg Forest Research Station (UFRS) of the National University of Mongolia (NUM) (48°16'24"N, 106°51'3"E, altitude: 1338 m), Batsumber district, Tov province using a 25-m tall tower (Fig. 1) over a larch forest on the permafrost area of northern Mongolia since January 2010. The UFRS is located 50 km north of Ulaanbaatar, the capital city of Mongolia. Fences protect 2 ha of the forest around the tower from grazing and illegal logging. The main forest types in the UFRS are larch (*L. sibirica* Ledeb.) forest, white birch (*Betula platyphylla* Suk) forest, and a mixed boreal forest including evergreen conifers (Otoda et al., 2012). In a mature stand near the UFRS without fire damage, the same as the forest around our tower, the total basal area was 30.89 m<sup>2</sup> ha<sup>-1</sup>, including 8.13 m<sup>2</sup> ha<sup>-1</sup> for *B. platyphylla* (birch), 18.42 m<sup>2</sup> ha<sup>-1</sup> for *L. sibirica* (larch), 4.18 m<sup>2</sup> ha<sup>-1</sup> for *Picea obovata* (spruce), and 0.16 m<sup>2</sup> ha<sup>-1</sup> for *Pinus sibirica* (pine) (Otoda et al., 2012). The average height and diameter at breast height of larch trees were 18.3 m and 33.2 cm, respectively. The average age of larch trees was 70–90 years and the maximum age of larch trees was about 300 years old. Large forest fires occurred near the UFRS in 1968, 1996, and 2005 (Otoda et al., 2012).



Fig. 1. Photo of the tower at Udleg Forest Research Station.

## 2.2. Observation methods and data

The air temperature and relative humidity was observed by hygrometer at 1.5 m (HMP45C, Vaisala Inc., Helsinki, Finland) and 27 m (WXT520, Vaisala Inc., Helsinki, Finland) above the ground. The wind speed and direction, air pressure, and precipitation were observed by a weather sensor at 27 m above the ground (WXT520, Vaisala Inc., Helsinki, Finland). The incoming and outgoing shortwave and longwave radiation (NR01, Hukseflux, Delft, Netherlands) and photosynthetically active radiation (ML-20P, Eiko, Tokyo, Japan) were observed at 5 and 27 m above the ground. The soil temperature was measured by platinum resistance sensors at depths of 0.2, 0.4, 0.8, 1.2, 1.8, 2.5, 3.5, and 4.5 m (107, Campbell, Logan, Utah, USA) and at depths of 0, 1, 2, 3, 4, 6, 8, and 10 m (TMC-HD and U12, Onset, Bourne, MA, USA). The sensors were calibrated (Ishikawa et al., 2005, 2012). The soil water content was measured using frequency domain reflectometry sensor at depths of 0.1, 0.3, 0.7, 0.9, 1.3, 1.8, and 2.3 m (EnviroSMART, Sentek Pty Ltd., Australia). This sensor measures the soil water content based on the difference of dielectric constant between the air (1) and the water (<81). There were no hydrometeorological data from January and February in 2010 (air temperature was gap-filled using sonic anemometer temperature using a linear regression with hygrometer data) due to instrumental failure, but there were no missing data in 2011 and 2012. All hydrometeorological data was sampled at 1-min intervals and averaged or totalized for 10 min. The interval camera (CH-IVCA13, Climatec Inc., Tokyo, Japan) for in situ phenological monitoring was set at 26 m on the top of the tower starting in March 2010. There were almost no missing interval camera data except from May to early August in 2011.

We also used the operational data to support our analysis. The normal climate value of air temperature and precipitation from 1981 to 2010 at Ulaanbaatar was obtained from the Japan Meteorological Agency (<http://www.data.jma.go.jp/gmd/cpd/db/monitor/nrmlist/>).

## 2.3. Data processing

We observed the 3-dimensional wind speed, air temperature, water vapor concentration, carbon dioxide concentration and air pressure with 10 Hz intervals with a sonic anemometer-thermometer (81000, RM Young, Michigan, USA) and open-path infrared gas analyzer (LI7500, Licor Inc., Lincoln, Nebraska, USA)



at 27.3 m above the ground. We calculated the sensible heat, latent heat, momentum, and carbon dioxide fluxes by the eddy covariance method using TK3 software (Mauder and Foken, 2011). We applied spike removal, cross wind correction (Liu et al., 2001), conversion of buoyancy flux into sensible heat flux, path-length for Moore correction (Moore, 1986), coordinate rotation, planar fit rotation (Wilczak et al., 2001), and WPL correction (Webb et al., 1980) for calculating fluxes by TK3. The calculated fluxes were evaluated based on the quality control scheme of TK3 for steady state, integral turbulence characteristics after Foken et al. (2004). The nighttime flux data under calm conditions was eliminated using a friction velocity  $u^*$  threshold algorithm (Reichstein et al., 2005). In this study we set the  $u^*$  threshold to 0.2 m/s because the annual NEE was not changed when the  $u^*$  threshold exceed 0.2 m/s. The  $u^*$  threshold value of 0.2 m/s in our study was similar to previous studies (e.g., Li et al., 2005; Nakai et al., 2008). For the energy, water, and carbon flux data, there was a data gap due to instrumental failure in early March, from late May to middle July, and in middle and late December in 2010. In 2011, there was a data gap for the flux data due to instrumental failure from January to early February and from late August to mid-September. In 2012, there was a data gap for the flux data due to instrumental failure from mid-March to mid-May and in the latter half of December. To estimate the daily and annual time scale fluxes, we applied the standardized gap-filling procedure (Falge et al., 2001; Reichstein et al., 2005) to fill the observation gaps in half-hourly flux data using the Flux Analysis Tool (FAP; Ueyama et al., 2012). The ratio of observed values to the gap-filled flux data was 65%, 68%, and 61% in 2010, 2011, and 2012, respectively. The rest of the flux data were estimated using a look-up table or linear regression model.

We defined the energy budget as follows:

$$R_n = H + LE + G + J \quad (1)$$

where  $R_n$ ,  $H$ ,  $LE$ ,  $G$ , and  $J$  are the net radiation at the surface, the sensible heat flux, the latent heat flux, the soil heat flux, and the change in heat storage in the canopy layer, respectively. The  $R_n$  was calculated from the 4-component radiometer observation. The  $H$  and  $LE$  were calculated by the eddy covariance method with necessary corrections as described above. The  $G$  was calculated from the observed values by a heat flux plate at several cm depth in the soil. According to Ohta et al. (2001), the  $J$  should be taken into account for the

analysis of diurnal variations; however, we discuss the daily energy balance in the same way as their study, and  $J$  is ignored as the storage of heat during the day is canceled by energy released during the night. In our site, the surface energy budget closure ratio,  $(H + LE)/(R_n - G)$  was 0.76–0.84, which corresponded to the average value of energy closure (0.8) at FLUXNET sites (Wilson et al., 2002). This suggests that the quality of our flux measurement was sufficient for the quantitative analysis of the energy and carbon budgets. Moreover, there was a homogeneous stand of larch trees northwest of the tower, the direction upwind for the prevailing winds.

We defined the carbon budget as:

$$NEE = -GPP + RE \quad (2)$$

where the NEE, GPP, and RE are the net ecosystem exchange, gross primary production, and ecosystem respiration, respectively. The NEE value is observed to be negative depending on the amount of carbon consumed from the atmosphere, whereas the value becomes positive depending on the amount of carbon released into the atmosphere. The NEE was calculated by the eddy covariance method with gap-filling and necessary corrections as described above. The flux partitioning for estimating GPP and RE from the NEE by the carbon dioxide flux ( $F_c$ ) data was applied using the FAP. The RE was calculated as the function of air temperature using nighttime  $F_c$  by the empirical model of Lloyd and Taylor (1994). The GPP was determined as the difference between the observed  $F_c$  and calculated RE using the FAP (Ueyama et al., 2012). We sometimes found an apparent off-season  $CO_2$  uptake in the calculated  $F_c$  by using open-path sensors when it was physiologically unreasonable to expect it (e.g., Burba et al., 2008; Ono et al., 2008; Amiro, 2010; Saigusa et al., 2012). We replaced all downward (negative value)  $F_c$  with 0 fluxes during the dormant season, defined as when the daily mean air temperature was less than 5 °C.

### 3. Results and discussion

#### 3.1. Hydrometeorological conditions

The inter-annual variation and seasonal variation of hydrometeorological conditions affect the energy, water, and carbon budget, which interact with each other. The annual mean air temperature was  $-0.13$  °C,  $-0.18$  °C, and  $-1.2$  °C in 2010, 2011, 2012, respectively. The time series of monthly mean air

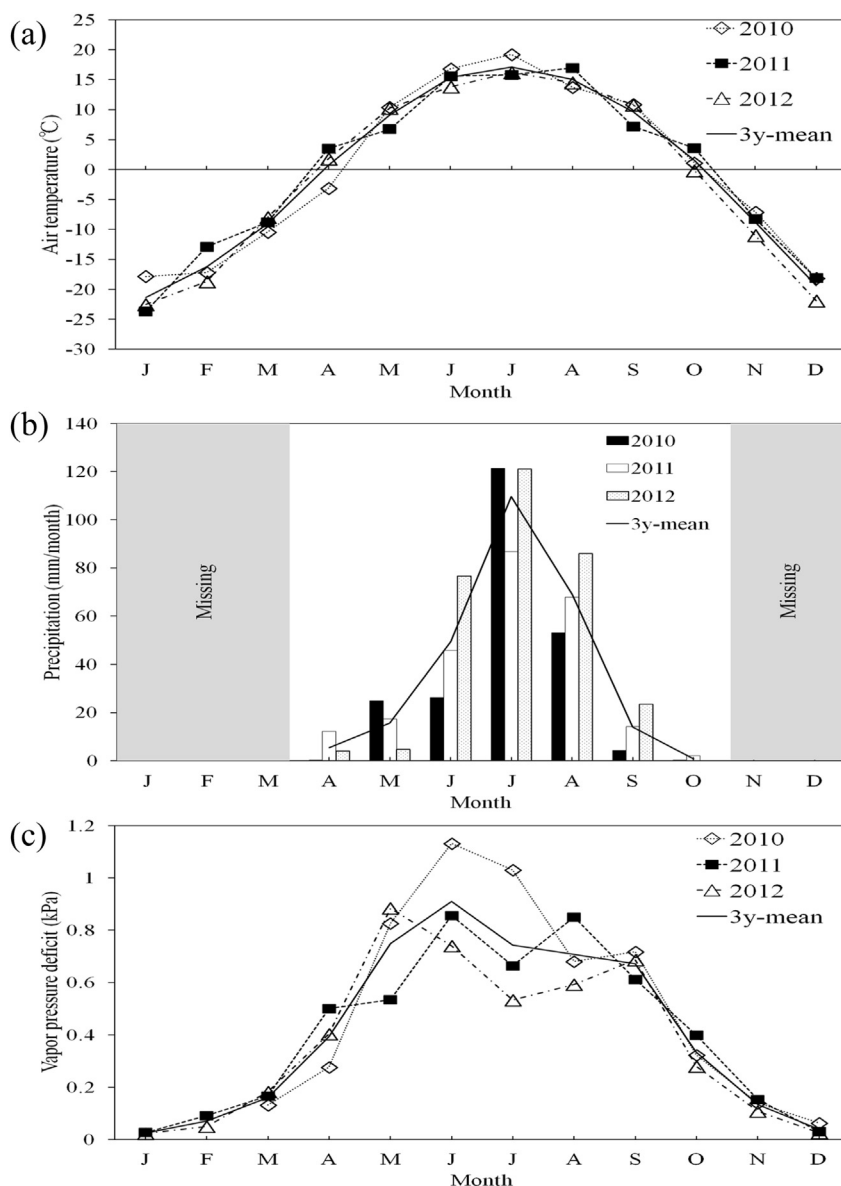


Fig. 2. Time series of (a) monthly mean air temperature, (b) monthly accumulated precipitation, and (c) monthly mean vapor pressure deficit from 2010 to 2012.

temperature ( $T_a$ ) from 2010 to 2012 is shown in Fig. 2a. The  $T_a$  in April 2010 was  $-3.1^{\circ}\text{C}$ , which was about  $3.8^{\circ}\text{C}$  lower than the 3-year mean (2010–2012), and  $4.9^{\circ}\text{C}$  lower than the normal mean (1981–2010)  $T_a$  at the Ulaanbaatar station. By the end of April 2010, more than 7.8 million head of livestock (17% of Mongolia’s livestock) had perished by “dzud” (an unprecedented loss of livestock; OCHA, 2010). The  $T_a$  in July 2010 was  $2.1^{\circ}$  higher than the 3-year mean.

The annual precipitation was 230 mm, 246 mm, and 317 mm in 2010, 2011, and 2012, respectively. Due to

instrumental failure, the winter precipitation (from November to March) might be missing. The nearest operational weather station from the UFRS is the Ulaanbaatar station which is 50 km south. The normal mean (1981–2010 mean) precipitation in winter (November to March) was 17.3 mm, which corresponds to about 6% of the annual precipitation (281 mm) at the Ulaanbaatar station. Fig. 2b shows the time series of monthly accumulated precipitation ( $P$ ) from 2010 to 2012. In June, July, August, and September 2012, the  $P$  was 27, 11, 17, and 10 mm

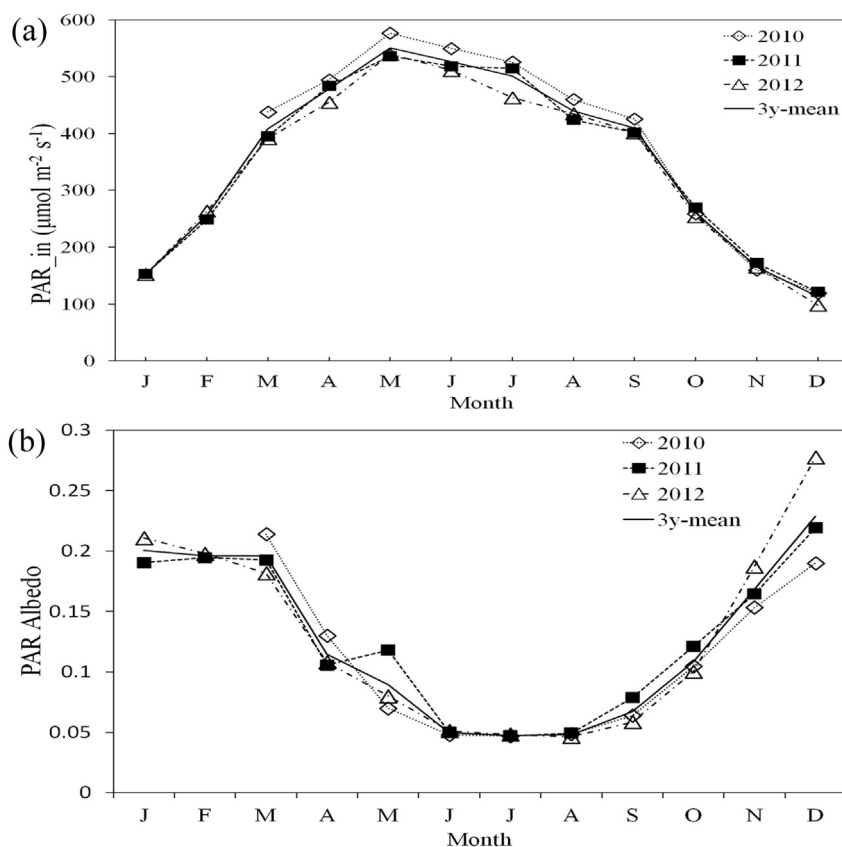


Fig. 3. Time series of (a) monthly mean incident photosynthetically active radiation (PAR) and (b) PAR albedo from 2010 to 2012.

higher than the 3-year mean, respectively. In 2010, the  $P$  was higher than the other years in May and the  $P$  in July 2010 was the same as in July 2012.

The vapor pressure deficit (VPD) is an important parameter for the energy and carbon budgets through the evapotranspiration and photosynthesis process. The time series of monthly mean VPD from 2010 to 2012 is shown in Fig. 2c. The VPD in April 2010 was lower by 0.1 kPa or less than the 3-year average, which was likely due to the low  $T_a$  in April 2010. The VPD in June and July 2010 was higher by 0.2 kPa or more than the 3-year mean, which was likely due to the higher  $T_a$  coinciding with lower precipitation in June and early July 2010. The VPD in May 2011 was lower by 0.2 kPa or less than the 3-year mean, which may relate to the lower  $T_a$  in May 2011. From June to August 2012, the VPD was lower by 0.1 or less than the 3-year mean, which may have been related to the higher  $P$  from June to August 2012.

The photosynthetically active radiation (PAR) at wavelengths ranging from 400 to 700 nm had a close relationship with photosynthesis. Kato and Tang (2008) indicated that the PAR and air temperature

were the most significant predictors of the annual NEE based on their multiple regression and stepwise analysis of  $\text{CO}_2$  flux observations at 49 sites in terrestrial Asia. The time series of incident monthly mean PAR from 2010 to 2012 is shown in Fig. 3a. The incident PAR from May to September in 2010 was  $24\text{--}63 \mu\text{mol m}^{-2} \text{s}^{-1}$  higher than the PAR in 2011 and

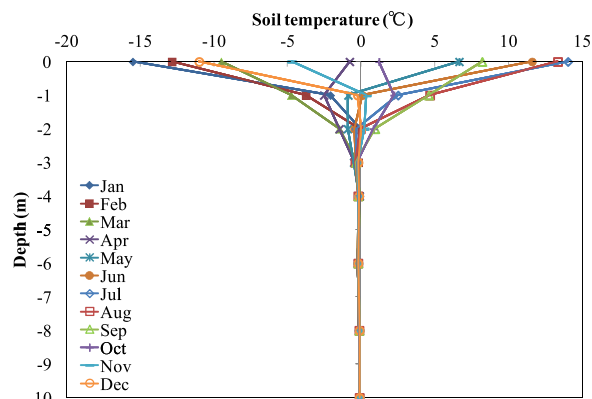


Fig. 4. Monthly mean soil temperature profile for the averaged values from 2010 to 2012.

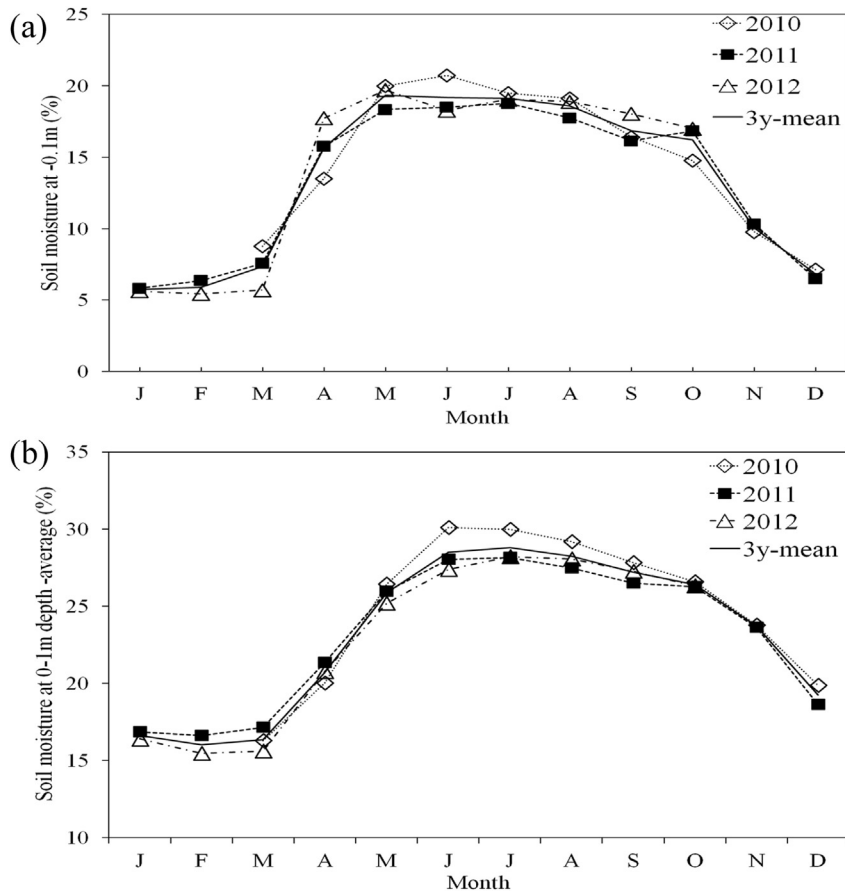


Fig. 5. Time series of monthly mean surface soil water content at (a) 0.1 m depth and (b) the average value for 0–1-m depths from 2010 to 2012.

2012. The incident PAR in June, August, and September in 2010 was higher than the other years, which was likely caused by lower precipitation in June and early July 2010. The PAR albedo (the ratio of the reflected PAR in the canopy to the incident PAR) is a good indicator of the leaf area index and stomatal conductance (Sakai et al., 1997). The time series of the PAR albedo from 2010 to 2012 is shown in Fig. 3b. From November to March, the PAR albedo was more than 0.15, which suggests that the surface was covered by snow. The PAR albedo dropped to less than 0.1 in May, except in 2011, and remained low until September, which suggests that leaves emerged in May, and the strong absorption of PAR by photosynthetically active leaves was maintained during this period. Using image analysis of an in situ camera at the top of the tower, we clarified the seasonal variation of the surface conditions and phenology of the larch forest. From November to March, there was continuous snow cover on the surface. In late May, larch leaves emerged and attained their mature size in July, and

then leaf senescence occurred in mid-September. These features corresponded with the seasonal variation in PAR albedo as shown in Fig. 3b.

To clarify the existence of the permafrost underground, the seasonal variation of the soil temperature profile from the 3-year (2010–2012) average is shown in Fig. 4. The soil temperature below a depth of 3 m was about  $-0.2$  to  $-0.9$  °C year round for more than 2 years, which suggests that there is permafrost below a depth of 3 m. As our observation of soil temperature was limited beyond 10 m depth, the thickness of the permafrost was unknown, but was at least 7 m, which the soil temperature was below 0 °C more than 2 years at depths from 3 m to 10 m according to our observation. The average thickness of the permafrost in the continuous and discontinuous zone in valleys and depressions is 50–100 m (Sharkhuu and Sharkhuu, 2012).

The soil water content in surface layers is the key parameter for evapotranspiration and photosynthesis. Fig. 5a shows the time series of monthly mean soil



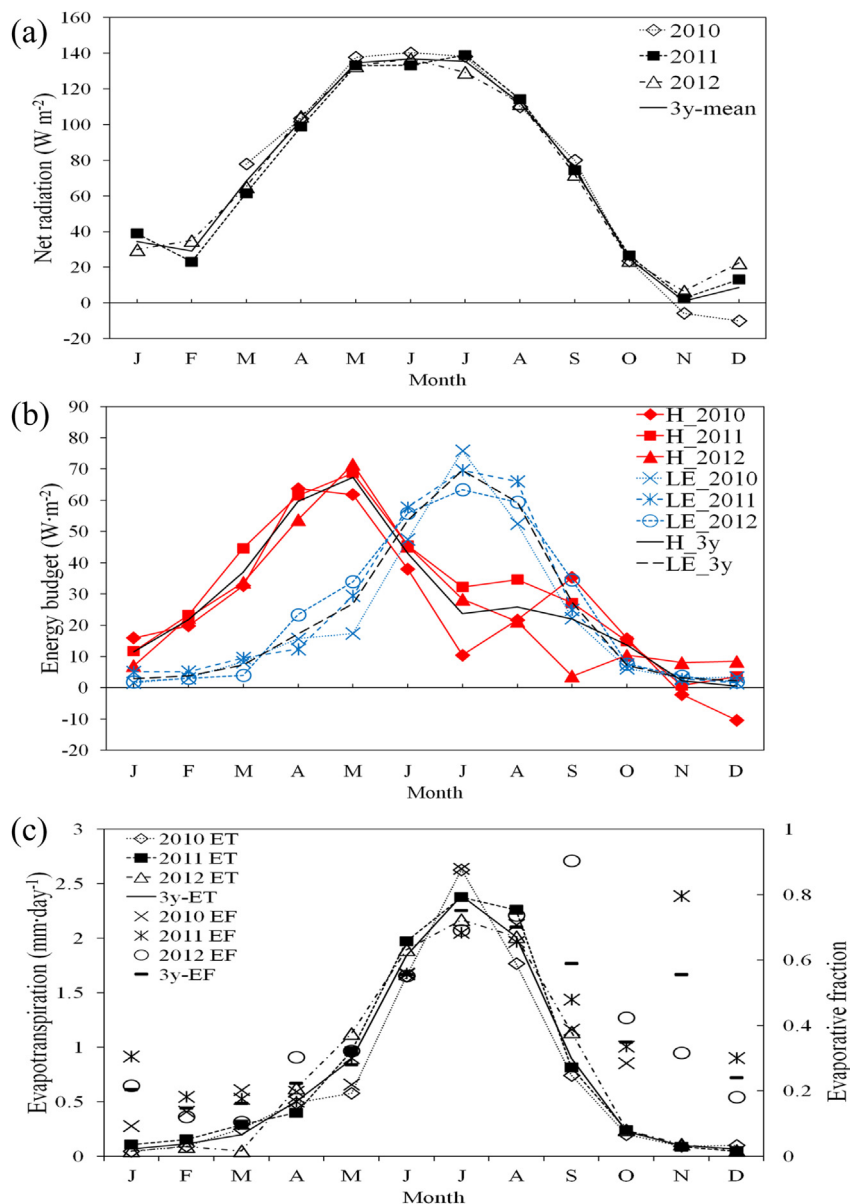


Fig. 6. Time series of (a) monthly mean net radiation ( $R_n$ ), (b) monthly mean sensible heat flux ( $H$ ) and latent heat flux ( $LE$ ), and (c) evapotranspiration ( $ET$ ) and evaporative fraction ( $EF$ ) from 2010 to 2012.

water content (SWC) at 0.1 m depth. From November to March, the SWC was less than 10% while it was more than 15% from May to October. As the soil water was frozen from November to March, the SWC showed low value due to the quite lower dielectric constant of the ice (3) than the liquid water (<81). The sensitivity of the SWC sensor for the ice is quite lower than the liquid water. The SWC in 2010 was about 2% higher than other years from May to August. The  $P$  in May 2010 was higher than other years and the  $P$  in July

was the same as in 2012. The higher SWC in May to August might be related to the higher  $P$ . The SWC in September 2012 was about 2% higher than the same time in other years, which was related to the larger  $P$  in August and September 2012 than other years. To clarify the contribution of SWC at the deeper layer, the average SWC at 0.1–1.0 m depth is shown in Fig. 5b. The SWC from June to August in 2010 was higher than other years. The seasonal pattern of SWC at 0.1 m and the average SWC at 0.1–1-m depths were similar.

Table 1

Comparison of albedo, evapotranspiration (ET), Bowen ratio, and evaporative fraction (EF) with other boreal forest sites.

Site	Species	Year	Albedo	ET (mm day <sup>-1</sup> )	Bowen ratio	EF
Udleg, Mongolia (48°15'N, 106°50'), This study	Larch ( <i>Larix siberica</i> )	2010–2012	0.22–0.40 (snow) 0.14–0.15 (Jun–Aug)	2.0–2.2 (Jun–Aug)	0.45–0.59 (Jun–Aug)	0.67 (Jun–Aug)
Yakutsuk, Russia (61°, 128°), Kelliher et al., 1997	Larch ( <i>Larix gmelinii</i> )	July, 1993	—	1.9 (14–27 July 1993)	1.24 (14–27 July 1993)	0.46 (14–27 July 1993)
Yakutsuk, Russia (62°05'N, 129°45'), Ohta et al., 2001, 2008	Larch ( <i>Larix cajanderii</i> )	1998–2006	0.22–0.27 (snow) 0.11–0.13 (no foliage) 0.20–0.22 (snow) 0.12–0.15 (Jun–Aug)	1.5–2.3 (May–Sep)	1.10 (Jun–Aug)	0.48 (May–Sep)
Tomakomai, Japan (42°44'N, 141°31'), Hirano et al., 2003	Larch ( <i>Larix kaempferi</i> )	2001	—	4.7 (Jun–Aug)	0.78 (Jun–Aug)	0.57 (Jun–Aug)
Hyytiälä, Finland (61°51'N, 24°17'E), Launiainen, 2010	Scots pine ( <i>Pinus sylvestris</i> L)	2000	—	1.4 (Jul–Aug)	0.62 (Jul–Aug)	0.62 (Jul–Aug)
Saskatchewan, Canada (53°37'N, 106°12'W), Amiro et al., 2006	Aspen ( <i>Populus tremuloides Michx.</i> )	2001–2002	—	2.5 (May–Sep)	0.4–0.9 (May–Sep)	—

### 3.2. Energy budget

As the  $R_n$  is an important parameter of the input energy to the surface, the time series of monthly mean net radiation is shown in Fig. 6a. The annual maximum  $R_n$  was about 140 W m<sup>-2</sup> and the minimum was 0 or about -10 W m<sup>-2</sup> in the observation period. The inter-annual variation of the  $R_n$  was small in the snow-free period (from April to October) while it was slightly greater in the snow-cover period (from November to March).

The partition of the  $H$  and LE is most important for clarifying the features of the energy budget. Fig. 6b

shows the time series of the  $H$  and LE. The annual maximum  $H$  was in May while the annual maximum LE was in July. From October to May, the average ratio of the  $H$  to the available energy ( $R_a$ :  $R_n - G$ ) was 0.46, while the average LE/ $R_a$  was 0.15, which shows that the  $H$  was the dominant component of the energy budget during this period. On the other hand, the average value of  $H/R_a$  was 0.28 from June to September while the average value of LE/ $R_a$  was 0.52 which shows that the LE was the dominant component of the energy budget during this period. The total  $P$  from May to September was more than 95% of the annual  $P$ . The large LE indicates large

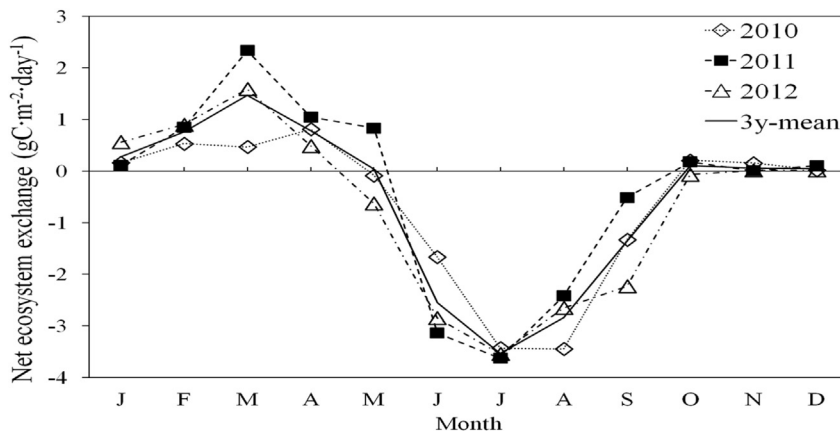


Fig. 7. Time series of monthly mean net ecosystem exchange from 2010 to 2012.

evapotranspiration, which is related to the high  $P$  and SWC from May to September. Fig. 6c shows the time series of evapotranspiration (ET) and evaporative fraction (EF; the ratio of LE to the sum of LE and  $H$ ). The 3-year mean ET from June to August was  $2.1 \text{ mm d}^{-1}$ . The ET in April and May 2012 was higher than the 3-year average, which may relate to higher SWC. The ET in July 2010 was higher than the 3-year average, which may relate to higher SWC. The ET in August 2011 was higher than the 3-year average, which was likely due to the high VPD. The ET in September 2012 was higher than the 3-year average, which may relate to the higher SWC. The mean EF from June to August was 0.67 (2010–2012 average) and ranged from 0.63 (2011) to 0.71 (2010), which was higher than the EF (0.48 average and range from 0.379 to 0.678) observed in a larch forest in Siberia (Ohta et al., 2008). The EF in July 2010 was about 0.9, which was about 0.2 higher than the EF in July 2011 and 2012. The EF in September 2012 was about 0.9, which was about twice the EF in 2010 and 2011, which was likely due to the higher  $P$  in September 2012 than in other years. The Bowen ratio ( $H/LE$ ) ranged from

0.13 to 0.81 from June to August with large interannual variation (figure was not shown). The summer (June, July, and August) mean Bowen ratio at our site (0.53) was much lower than at the other larch site (1.0–1.4; Schulze et al., 1999; Ohta et al., 2001). Ohta et al. (2008) pointed out that the Bowen ratio was lower when the SWC was high. At our site, the summertime SWC remained steady at approximately 20%, which was higher than the SWC observed at the larch forest in Siberia (Ohta et al., 2008). This suggests that the continuously higher SWC kept the Bowen ratio lower and the EF higher than at the other larch site.

To clarify the characteristics of the energy budget at our site, the albedo and evapotranspiration-related parameters are compared in Table 1. The average albedo (0.22–0.40) at the UFRS during the snow-cover period (from November to March) and the growing season (from June to August) was similar to those at a Siberian larch site (0.22–0.27; Ohta et al., 2008) and a Japanese larch site (0.20–0.22; Hirano et al., 2003), while the maximum albedo during the snow-cover season was higher than at the other sites (Ohta et al., 2008; Hirano et al., 2003). The ET

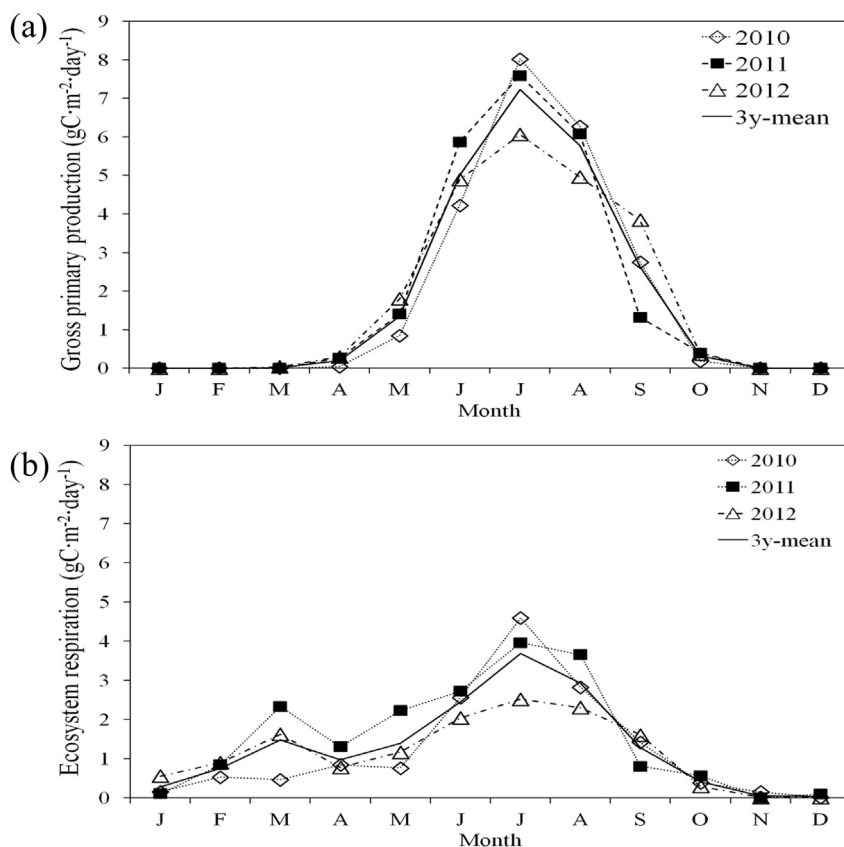


Fig. 8. Time series of (a) monthly mean gross primary production and (b) monthly mean ecosystem respiration from 2010 to 2012.

(2.0–2.2 mm d<sup>-1</sup>) at the UFRS was higher than the Scots pine site (1.4 mm d<sup>-1</sup>; Launiainen, 2010) or similar to the Siberian larch site (1.9 mm d<sup>-1</sup>; Kelliher et al., 1997; 1.5–2.3 mm d<sup>-1</sup>; Ohta et al., 2008) and the aspen forest site (2.5 mm d<sup>-1</sup>; Amiro et al., 2006) but lower than the Japanese larch site (4.7 mm d<sup>-1</sup>; Hirano et al., 2003). The growing season Bowen ratio was lower than at the other larch sites, and the growing season EF was higher than at the other larch sites, but lower than that for a Scots pine forest in Finland. This suggests that the larch in Mongolia partitioned more energy into the latent heat flux than at the other larch sites, which is related to the lack of a reduction in the SWC during the growing season.

### 3.3. Carbon budget in response to hydrometeorological conditions

The time series of the NEE is shown in Fig. 7. A large carbon uptake (negative values of NEE) was noted from June to September for all years when the LE was greater than or similar to the *H* in the energy budget (Fig. 6b). In May 2011, the NEE was positive, which means that carbon was released from the surface while the NEE in the other years was negative, which means that carbon was taken up. In May 2011, the PAR albedo was higher than the other years and the *T<sub>a</sub>* was lower than the other years. It is likely that the cooler climate suppressed the photosynthetic activity, and thus the leaves did not emerge in May 2011. In June 2010, the NEE was higher (lower absolute value) by 0.89 than the 3-year mean. The *P* and VPD in June

2010 were the lowest in the 3 years while the *T<sub>a</sub>*, incident PAR, and SWC were higher than that other years. The reason for the high NEE was unclear. As the flux measurement failed in June 2010, a gap-filled value was used. Therefore, there might be some error in these data. In August 2010, the NEE was more negative by 0.6 gC m<sup>2</sup> d<sup>-1</sup> than the 3-year mean, while the incident PAR, VPD, and EF was higher than the 3-year mean. This suggests that the higher incident PAR enhanced photosynthesis and transpiration. In September 2012, the NEE was lower (higher absolute value) by 0.87 gC m<sup>2</sup> d<sup>-1</sup> than the 3-year mean. The EF in September 2012 was about double that of the other years. The SWC and *P* in September 2012 were higher than that in other years. These were favorable conditions for active photosynthesis. The daily integrated NEE ranged between -6.9 gC m<sup>2</sup> d<sup>-1</sup> (10 July 2011) and 5.5 gC m<sup>2</sup> d<sup>-1</sup> (23 March 2011). The maximum carbon uptake in July (-6.9 gC m<sup>2</sup> d<sup>-1</sup>) at our site was larger than the carbon uptake observed at another larch site in Mongolia (-4.0 gC m<sup>2</sup> d<sup>-1</sup>; Li et al., 2005) and at a larch site in East Siberia (-4.5 gC m<sup>2</sup> d<sup>-1</sup>; Dolman et al., 2004) and in Central Siberia (-2.0 gC m<sup>2</sup> d<sup>-1</sup>; Nakai et al., 2008).

Fig. 8a and b shows the time series of the GPP and RE, respectively. The GPP and RE were estimated by the flux-partition method shown in Section 2. In June 2011, the GPP was larger by 0.87 gC m<sup>2</sup> d<sup>-1</sup> than the 3-year mean. The VPD in 2011 was the highest of the 3 years. This suggests that the higher GPP may relate to higher atmospheric demand. In July and August 2012, the GPP was lower by 1.2 and 0.8 gC m<sup>2</sup> d<sup>-1</sup> than the

Table 2

Comparison of the net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (RE) with other boreal forest sites.

Site	Species	Year	NEE (gC m <sup>-2</sup> y <sup>-1</sup> )	GPP (gC m <sup>-2</sup> y <sup>-1</sup> )	RE (gC m <sup>-2</sup> y <sup>-1</sup> )
Udleg, Mongolia (48°15'N, 106°50'), This study	Larch ( <i>Larix siberica</i> )	2010–2012	-132 to -257	681–703	423–571
Mongomorit, Mongolia (48°21'N, 108°39'), Li et al., 2005; Hirata et al., 2008	Larch ( <i>Larix siberica</i> )	2003–2005	-120 to -150	450–600	340–450
Tura, Russia (64°12'N, 100°27'), Nakai et al., 2008	Larch ( <i>Larix gmelinii</i> )	2004	-76 (Jun–Sep)	—	—
Yakutsuk, Russia (62°05'N, 129°45'), Dolman et al., 2004	Larch ( <i>Larix cajanderii</i> )	2001	-160	—	—
Laoshan, China (45°02'N, 127°34'), Wang et al., 2008	Larch ( <i>Larix gmelinii</i> )	2004	-146	1351	1207
Tomakomai, Japan (42°44'N, 141°31'), Hirata et al., 2007	Larch ( <i>Larix kaempferi</i> )	2001–2003	-164 to -249	1636–1742	1413–1478
Hyttiala, Finland (61°51'N, 24°17'E), Lagergren et al., 2008	Scots pine ( <i>Pinus sylvestris</i> L.)	2000–2005	-199	1047	—
Saskatchewan, Canada (53°37'N, 106°12'W), Amiro et al., 2006	Aspen ( <i>Populus tremuloides Michx.</i> )	2001–2002	-139 to -361	—	—

3-year mean, respectively. The VPD in July and August 2012 was lower by 0.2 kPa and 0.1 kPa than the 3-year mean, respectively. The  $P$  in July and August 2012 was higher by 11 mm and 17 mm than the 3-year mean, respectively. This suggests that the higher  $P$  and lower VPD suppressed photosynthetic activity. In September 2012, the GPP was 2 and 3 times larger than the GPP in 2010 and 2011, respectively. The  $P$  in September 2012 was 2 and 6 times larger than the  $P$  in September 2010 and 2011, respectively, and the surface SWC in September 2012 was higher than other years. This suggests that the wet surface raised the photosynthesis activity and ET compared to the other years.

As described in Section 2.3, the RE was calculated as a function of air temperature using nighttime  $F_c$  by the empirical model of Lloyd and Taylor (1994). Therefore, air temperature is the most important factor.

The RE in June, July, and August in 2012 was lower by 0.4, 1.2, and 0.6  $\text{gC m}^{-2} \text{d}^{-1}$  than the 3-year mean. The  $T_a$  and incident PAR from June to August 2012 were lower than in other years, while the  $P$  was the highest among the 3 years. This suggests that the lower RE from June to August 2012 may be related to a cooler climate. The RE in August 2011 was higher than in the other years. It is likely to be related to the higher  $T_a$  due to lower precipitation from June to August 2011 than in the other years.

Table 2 compares the annual carbon budget with those of other larch sites. The annual NEE in 2011 ( $-132 \text{ gC m}^{-2} \text{y}^{-1}$ ) was similar to that of larch trees at other larch sites in Mongolia ( $-120$  to  $-150 \text{ gC m}^{-2} \text{y}^{-1}$ ; Li et al., 2005; Hirata et al., 2008), in Siberia ( $-160 \text{ gC m}^{-2} \text{y}^{-1}$ ; Dolman et al., 2004), and in China ( $-146 \text{ gC m}^{-2} \text{y}^{-1}$ ; Wang et al., 2008). The annual NEEs at our site in 2010 and 2012 ( $-235$  and

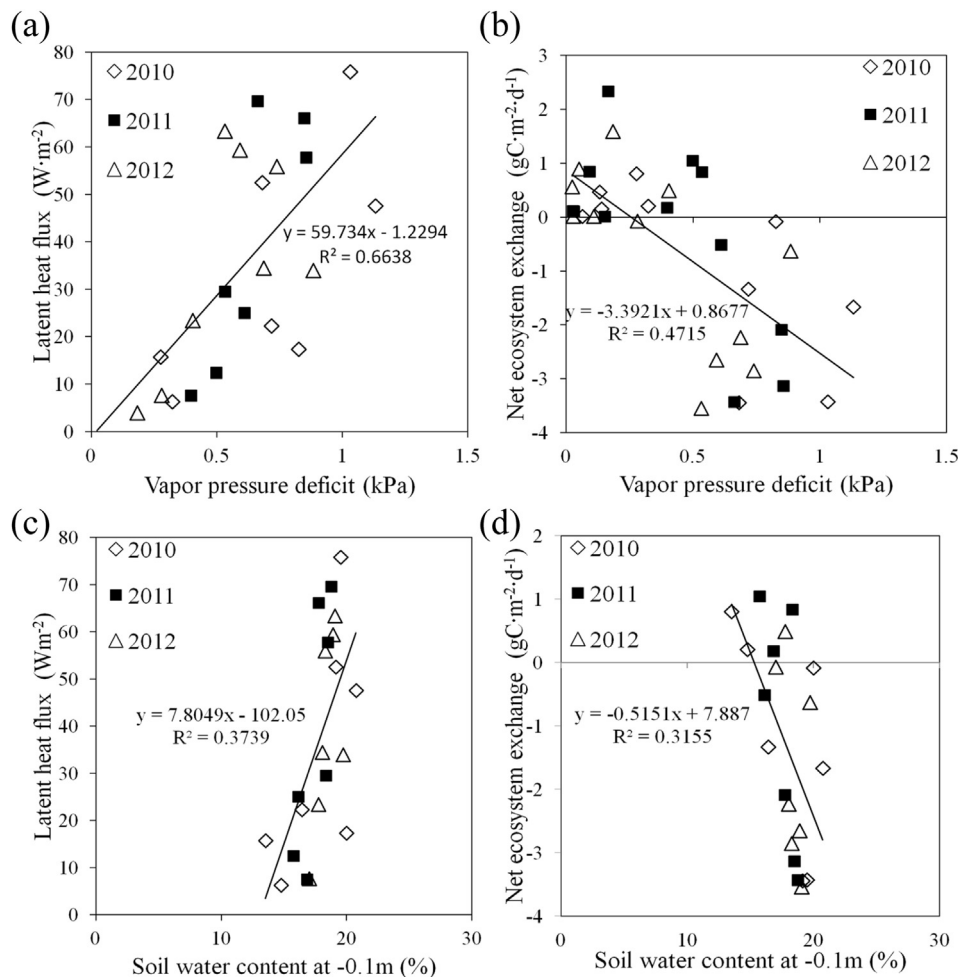


Fig. 9. Response of (a) latent heat flux (LE) and (b) net ecosystem exchange (NEE) to the vapor pressure deficit, and the response of (c) LE and (d) NEE to the soil water content.



$-257 \text{ gC m}^2 \text{ y}^{-1}$ ) were similar to that of a Japanese larch forest ( $-249 \text{ gC m}^2 \text{ y}^{-1}$ ; Hirata et al., 2007) and aspen forest in Canada ( $-250 \pm 67 \text{ gC m}^2 \text{ y}^{-1}$ ; Amiro et al., 2006). The average NEE over the 3 years in our study ( $-208 \pm 67 \text{ gC m}^2 \text{ y}^{-1}$ ) was similar to that of a Scots pine forest in Finland ( $-199 \pm 67 \text{ gC m}^2 \text{ y}^{-1}$ ; Lagergren et al., 2008) but more negative than the value in a previous study of a deciduous needleleaf forest ( $-144.7 \pm 49.8 \text{ gC m}^2 \text{ y}^{-1}$ ; Kato and Tang, 2008) and in a boreal semiarid climate ( $-178 \text{ gC m}^2 \text{ y}^{-1}$ ; Luyssaert et al., 2007). The GPP ( $680\text{--}702 \text{ gC m}^2 \text{ y}^{-1}$ ) at our site was smaller than in Chinese ( $1351 \text{ gC m}^2 \text{ y}^{-1}$ ; Wang et al., 2008) and Japanese ( $1636\text{--}1742 \text{ gC m}^2 \text{ y}^{-1}$ ; Hirata et al., 2007) larch sites and the Scots pine site ( $1047 \text{ gC m}^2 \text{ y}^{-1}$ ; Lagergren et al., 2008). The annual RE ranged from 423 to 571  $\text{gC m}^2 \text{ y}^{-1}$ . As our site is located on a gentle slope ( $5^\circ$ ), the nighttime respiration might flow downslope, making it difficult to capture at the top of the tower. Therefore, there is a possibility of the underestimation of nighttime respiration. However, it is difficult to estimate that amount with our instruments. The average GPP during the 3 years of our study was much smaller than the GPP of a deciduous needleleaf forest ( $968.3 \pm 458.3 \text{ gC m}^2 \text{ y}^{-1}$ ; Kato and Tang, 2008) and a boreal semiarid climate ( $1201 \pm 23 \text{ gC m}^2 \text{ y}^{-1}$ ; Luyssaert et al., 2007).

To improve the understanding of the energy and carbon processes, we investigated the response of the LE and NEE to hydrometeorological conditions. Fig. 9a and b shows the response of the LE and NEE to the VPD, respectively. There was a significant positive correlation between the VPD and LE ( $r = 0.81$  ( $r^2 = 0.66$ ),  $p < 0.01$ ), and significant negative correlation between the VPD and NEE ( $r = -0.69$  ( $r^2 = 0.47$ ),  $p < 0.01$ ). This suggests that the VPD was the controlling factor for both the LE and NEE. Li et al. (2005) pointed out that NEE was reduced when VPD was high (1.2 kPa for the daily NEE); there was no such reduction in our analysis. As we used monthly values, the maximum VPD was less than 1.2 kPa. Fig. 9c and d shows the response of the LE and NEE to the SWC, respectively. As the sensitivity of the SWC during the frozen soil period from November to March was quite lower than the liquid soil water period from April to October, we removed the points during the frozen soil period from Fig. 9c and d. There was a significant positive correlation between the SWC and LE ( $r = 0.61$  ( $r^2 = 0.37$ ),  $p < 0.01$ ), and a significant negative correlation between the SWC and NEE ( $r = -0.56$  ( $r^2 = 0.32$ ),  $p < 0.01$ ). This suggests that the SWC was the controlling factor for both the LE and

NEE. The relation between the daily NEE and SWC was not linear, and drought stress caused by low soil water content was not an important factor for the NEE during the growing season at another larch site in Mongolia (Li et al., 2005). As we used the monthly value, the linear response of the NEE to the SWC might be more than that found by using scattered daily values.

#### 4. Conclusions

We measured the interannual variation and seasonal variation of hydrometeorological conditions, and the energy and carbon budgets of a larch forest on permafrost in northeastern Mongolia based on 3 years of observations (2010–2012). The annual mean  $T$  and annual  $P$  ranged from  $-0.13^\circ\text{C}$  to  $-1.3^\circ\text{C}$  and from 230 mm to 310 mm, respectively. The VPD in June and July 2010 was larger than other years, which was probably caused by the higher air temperature and lower precipitation in June and early July 2010. The PAR in June and July 2010 was larger than in other years, which was probably caused by lower precipitation in June and early July 2010. There was permafrost starting at a depth of 3 m according to the long-term observation of a soil temperature profile. From November to March, the SWC was less than 10%, while it was about 20% from May to October when most of the annual  $P$  was provided. The  $H$  was the dominant component of the energy budget from October to May while the LE was dominant from June to September. The Bowen ratio was less than 1.0 from June to September when the NEE showed large carbon uptake coinciding with high precipitation and a high SWC. The annual NEE, GPP, and RE were  $-131$  to  $-257 \text{ gC m}^2 \text{ y}^{-1}$ ,  $681\text{--}703 \text{ gC m}^2 \text{ y}^{-1}$ , and  $423\text{--}571 \text{ gC m}^2 \text{ y}^{-1}$ , respectively. Differences in the seasonal pattern of  $T_a$ ,  $P$ , and VPD affected the annual energy and carbon budgets of the 3 years. There was a significant positive correlation between the VPD and LE ( $r = 0.81$  ( $r^2 = 0.66$ ),  $p < 0.01$ ), and a significant negative correlation between the VPD and NEE ( $r = -0.69$  ( $r^2 = 0.47$ ),  $p < 0.01$ ). There was a significant positive correlation between the SWC and LE ( $r = 0.61$  ( $r^2 = 0.37$ ),  $p < 0.01$ ), and a significant negative correlation between the SWC and NEE ( $r = -0.56$  ( $r^2 = 0.32$ ),  $p < 0.01$ ).

In our site, we measured the growth in diameter of trees at breast height using a dendrometer and tree ring core samples, and used a sap flow meter to measure the transpiration of larch trees. Further analysis using these

data may help to improve our understanding of the biological processes of Mongolian larch trees.

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## Appendix A. Supplementary material

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.polar.2013.12.004>.

## References

- Amiro, B., 2010. Estimating annual carbon dioxide eddy fluxes using open-path analysers for cold forest sites. *Agric. For. Meteorol.* 150, 1366–1372.
- Amiro, B.D., Barr, A.G., Black, T.A., Iwashita, H., Kljun, N., McCaughey, J.H., Morgenstern, K., Murayama, S., Nesic, Z., Orchansky, A.L., Saigusa, N., 2006. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agric. For. Meteorol.* 136, 237–251.
- Baldocchi, D., Francis, M., Kelliher, T., Black, A., Jarvis, P., 2000. Climate and vegetation on boreal zone energy exchange. *Glob. Change Biol.* 6 (Suppl. 1), 69–83.
- Batima, P., Natsgadorj, L., Gombluudev, P., Erdenetsetseg, B., 2005. Observed climate change in Mongolia. In: *Assessments of Impacts and Adaptations to Climate Change Working Paper*, vol. 12, pp. 1–26.
- Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and climate benefits of forests. *Science* 320, 1444. <http://dx.doi.org/10.1126/science.1155121>.
- Burba, G.G., McDermitt, D.K., Grelle, A., Anderson, D.J., Xu, L.K., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO<sub>2</sub> flux from open-path gas analyzers. *Glob. Change Biol.* 14, 1854–1876.
- Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., Zhang, X., 2007. Couplings between changes in the climate system and biogeochemistry. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 499–587.
- Dolman, A.J., Maximov, T.C., Moors, E.J., Maximov, A.P., Elbers, J.A., Kononov, A.V., Waterloo, M.J., van der Molen, M.K., 2004. Net ecosystem exchange of carbon dioxide and water of far eastern Siberian Larch (*Larix cajanderii*) on permafrost. *Biogeosciences* 1, 133–146.
- Dulamsuren, C., Hauck, M., Bader, M., Osokhjargal, D., Oyungerel, S., Nyambayar, S., Runge, M., Leuschner, C., 2008. Water relations and photosynthetic performance in *Larix sibirica* growing in the forest–steppe ecotone of northern Mongolia. *Tree Physiol.* 29, 99–110.
- Dulamsuren, C., Hauck, M., Khishigjargal, M., Leuschner, H.H., Leuschner, C., 2010. Diverging climate trends in Mongolian taiga forests influence growth and regeneration of *Larix sibirica*. *Oecologia* 163, 1091–1102. <http://dx.doi.org/10.1007/s00442-010-1689-y>.
- Dulamsuren, C., Hauck, M., Leuschner, H.H., Leuschner, C., 2011. Climate response of tree-ring width in *Larix sibirica* growing in the drought-stressed forest–steppe ecotone of northern Mongolia. *Ann. For. Sci.* 68, 275–282. <http://dx.doi.org/10.1007/s13595-011-0043-9>.
- Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol.* 107, 43–69.
- Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B.D., Munger, J.W., 2004. Post-field data quality control. In: Lee, X., et al. (Eds.), *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis*. Kluwer, Dordrecht, pp. 181–208.
- Hirano, T., Hirata, R., Fujinuma, Y., Saigusa, N., Yamamoto, S., Harazono, Y., Takada, M., Inukai, K., Inoue, G., 2003. CO<sub>2</sub> and water vapor exchange of a larch forest in northern Japan. *Tellus* 55B, 244–257.
- Hirata, R., Hirano, T., Saigusa, N., Fujinuma, Y., Inukai, K., Kitamori, Y., Yamamoto, S., 2007. Seasonal and interannual variations in carbon dioxide exchange of a temperate larch forest. *Agric. For. Meteorol.* 147, 110–124.
- Hirata, R., Saigusa, N., Yamamoto, S., Ohtani, Y., Ide, R., Asanuma, J., Gamo, M., Hirano, T., Kondo, H., Kosugi, Y., Li, S.G., Nakai, Y., Takagi, K., Tani, M., Wang, H., 2008. Spatial distribution of carbon balance in forest ecosystems across East Asia. *Agric. For. Meteorol.* 148, 761–775.
- Ishikawa, M., Sharkhuu, N., Zhang, Y., Kadota, T., Ohata, T., 2005. Ground thermal and moisture conditions at the southern boundary of discontinuous permafrost, Mongolia. *Permafrost Periglac. Process.* 16, 209–216. <http://dx.doi.org/10.1002/ppp.483>.
- Ishikawa, M., Sharkhuu, N., Jambaljav, Y., Davaa, G., Yoshikawa, K., Ohata, T., 2012. Thermal state of Mongolian permafrost. In: Hinkel, K.M. (Ed.), *Proceedings of the Tenth International Conference on Permafrost*. The Northern Publisher, Salekhard, Russia, pp. 173–178.
- Kato, T., Tang, Y., 2008. Spatial variability and major controlling factors of CO<sub>2</sub> sink strength in Asian terrestrial ecosystems: evidence from eddy covariance data. *Glob. Change Biol.* 14, 2333–2348. <http://dx.doi.org/10.1111/j.1365-2486.2008.01646.x>.

- Kelliher, F.M., Hollinger, D.Y., Schulze, E.-D., Vygodskaya, N.N., Byers, J.N., Hunt, J.E., McSeveny, T.M., Milukova, I., Sogatchev, A., Varlargin, A., Ziegler, W., Arneth, A., Bauer, G., 1997. Evaporation from an eastern Siberian larch forest. *Agric. For. Meteorol.* 85, 135–147.
- Lagergren, F., Lindorth, A., Dellwik, E., Ibrom, A., Lankreijer, H., Launiainen, S., Molder, M., Kolar, P., Pilegaard, K., Vesala, T., 2008. Biophysical controls on CO<sub>2</sub> fluxes of three Northern forests based on long-term eddy covariance data. *Tellus* 60B, 143–152.
- Launiainen, S., 2010. Seasonal and inter-annual variability of energy exchange above a boreal Scots pine forest. *Biogeosciences* 7, 3921–3940.
- Li, S.G., Asanuma, J., Kotani, A., Eugster, W., Davaa, G., Oyunbaatar, D., Sugita, M., 2005. Year-round measurements of net ecosystem CO<sub>2</sub> flux over a montane larch forest in Mongolia. *J. Geophys. Res.* 110, D09303. <http://dx.doi.org/10.1029/2004JD005453>.
- Li, S.G., Tsujimura, M., Sugimoto, A., Sasaki, L., Davaa, G., Oyunbaatar, D., Sugita, M., 2006. Seasonal variations in oxygen isotope composition of waters for a montane larch forest in Mongolia. *Trees* 20, 122–130.
- Li, S.G., Romero-Saltos, H., Tsujimura, M., Sugimoto, A., Sasaki, L., Davaa, G., Oyunbaatar, D., 2007a. Plant water sources in the cold semiarid ecosystem of the upper Kherlen River catchment in Mongolia: a stable isotope approach. *J. Hydrol.* 333, 109–117.
- Li, S.G., Tsujimura, M., Sugimoto, A., Davaa, G., Oyunbaatar, D., Sugita, M., 2007b. Temporal variation of  $\delta^{13}\text{C}$  of larch leaves from a montane boreal forest in Mongolia. *Trees* 21, 479–490.
- Liu, H., Peters, G., Foken, T., 2001. New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer. *Bound. Layer Meteorol.* 100, 459–468.
- Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. *Funct. Ecol.* 8, 315–323.
- Luyssaert, S., Inglima, I., Jungs, M., et al., 2007. CO<sub>2</sub> balance of boreal, temperate, and tropical forests derived from a global database. *Glob. Change Biol.* 13, 2509–2537. <http://dx.doi.org/10.1111/j.1365-2486.2007.01439.x>.
- Mauder, M., Foken, T., 2011. Documentation and instruction manual of the eddy-covariance software package TK3 Universität Bayreuth, Abteilung Mikrometeorologie. *Arbeitsergebnisse*. ISSN: 1614-8924 46, 60.
- Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. *Bound. Layer Meteorol.* 37, 17–35.
- Nakai, Y., Matsuura, Y., Kajimoto, T., Abaimov, A.P., Yamamoto, S., Zyryanova, O.A., 2008. Eddy covariance CO<sub>2</sub> flux above a Gmelin larch forest in continuous permafrost of central Siberia during a growing season. *Theor. Appl. Climatol.* 93, 133–147. <http://dx.doi.org/10.1007/s00704-007-0337-x>.
- OCHA (United Nations Office for the Coordination of Humanitarian Affairs), 2010. Mongolia Dzud Appeal. United Nations, New York.
- Ono, K., Miyata, A., Yamada, T., 2008. Apparent downward CO<sub>2</sub> flux observed with open-path eddy covariance over a non-vegetated surface. *Theor. Appl. Climatol.* 92, 195–208.
- Ohta, T., Hiyama, T., Tanaka, H., Kuwada, T., Maximov, T.C., Ohata, T., Fukushima, Y., 2001. Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. *Hydrol. Process.* 15, 1459–1476.
- Ohta, T., Maximov, T.C., Dolman, A.J., Nakai, T., van der Molen, M.K., Kononov, A.V., Maximov, A.P., Hiyama, T., Iijima, Y., Moors, E.J., Tanaka, H., Toba, T., Yabuki, H., 2008. Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006). *Agric. For. Meteorol.* 148, 1941–1953.
- Otoda, T., Doi, T., Sakamoto, K., Hirobe, M., Baatarbileg, N., Yoshikawa, K., 2012. Frequent fires may alter the future composition of the boreal forest in northern Mongolia. *J. For. Res.* <http://dx.doi.org/10.1007/s10310-012-0345-2>.
- Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautanen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. *Science* 333, 988–993. <http://dx.doi.org/10.1126/science.1201609>.
- Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Glob. Change Biol.* 11, 1424–1439.
- Saigusa, N., Li, S.G., Kwon, H., Takagi, K., Zhang, L.M., Ide, R., Ueyama, M., Asanuma, J., Choi, Y.J., Chun, J.H., Han, S.J., Hirano, T., Hirata, R., Kang, M., Kato, T., Kim, J., Li, Y.N., Maeda, T., Miyata, A., Mizoguchi, Y., Murayama, S., Nakai, Y., Ohta, T., Saitoh, T.M., Wang, H.M., Yu, G.R., Zhang, Y.P., Zhao, F.H., 2012. Dataset of CarboEastAsia and uncertainties in the CO<sub>2</sub> budget evaluation caused by different data processing. *J. For. Res.* 18, 41–48. <http://dx.doi.org/10.1007/s10310-012-0378-6>.
- Sakai, R.K., Fitzjarrald, D.R., Moore, K.E., 1997. Detecting leaf area and surface resistance during transition seasons. *Agric. For. Meteorol.* 84, 273–284.
- Schulze, E.D., Lloyd, J., Kelliher, F.M., Wirth, C., Rebmann, C., Luhker, B., Mund, M., Knohl, A., Milyukova, M., Schulze, W., Ziegler, W., Varlargin, A.B., Sogachev, A.F., Valentini, R., Dore, S., Grigoriev, S., Kolle, O., Panforyorov, M.I., Tchebakova, N., Vygodskaya, N.N., 1999. Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink – a synthesis. *Glob. Change Biol.* 5, 703–722.
- Sellers, P.J., Hall, F.G., Magolis, H., Kelly, B., Baldocchi, D., den Hartog, G., Cihlar, J., Ryan, M.G., Goodison, B., Crill, P.M., Ranson, K.J., Lattersmaier, D.P., Wickland, D.E., 1995. The Boreal Ecosystem-Atmosphere Study (BOREAS): an overview and early results from the 1994 field year. *Bull. Am. Meteorol. Soc.* 76, 1549–1577.
- Sellers, P.J., Hall, F.G., Kelly, R.D., Black, A., Baldocchi, D., Berry, J., Ryan, M., Ranson, K.J., Crill, P.M., Lattersmaier, D.P., Magolis, H., Cihlar, J., Newcomer, J., Fitzjarrald, D., Jarvis, P.G., Gower, S.T., Halliwell, D., Williams, D., Goodison, B., Wickland, D.E., Guertin, F.E., 1997. BOREAS in 1997: experiment overview, scientific results, and future directions. *J. Geophys. Res.* 102 (D24), 28,731–28,769.
- Sharkhuu, N., Sharkhuu, A., 2012. Effects of climate warming and vegetation cover on permafrost of Mongolia. In: Werger, M.J.A., van Staaldunen, M.A. (Eds.), *Eurasian Steppes, Ecological Problems and Livelihoods in a Changing World*. Springer, Dordrecht, Heidelberg, New York, and London, pp. 445–472.
- Solomon, S., Qin, D., Manning, M., Alley, R.B., Bernsten, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M.,

- Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A., Wratt, D., 2007. Technical summary. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), *Climate Change, 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 19–91.
- Sugimoto, A., Yanagisawa, N., Naito, D., Fujita, N., Maximov, T.C., 2002. Importance of permafrost as a source of water for plants in east Siberian taiga. *Ecol. Res.* 17, 493–503.
- Sugimoto, A., Naito, D., Yanagisawa, N., Ichiyanagi, K., Kurita, N., Kubota, J., Kotake, T., Ohata, T., Maximov, T.C., Fedorov, A.N., 2003. Characteristics of soil moisture in permafrost observed in East Siberian taiga with stable isotopes of water. *Hydrol. Process.* 17, 1073–1092.
- Tsogtbaatar, J., 2004. Deforestation and reforestation needs in Mongolia. *For. Ecol. Manage.* 201, 57–63.
- Ueyama, M., Hirata, R., Mano, M., Hamotani, K., Harazono, Y., Hirano, T., Miyata, A., Takagi, K., Takahashi, Y., 2012. Influences of various calculation options on heat, water and carbon fluxes determined by open- and closed-path eddy covariance methods. *Tellus B* 64, 19048. <http://dx.doi.org/10.3402/tellusb.v64i0.19048>.
- Wang, H., Saigusa, N., Zu, Y., Wang, W., Yamamoto, S., Kondo, H., 2008. Carbon fluxes and their response to environmental variables in a Dahurian larch forest ecosystem in northeast China. *J. For. Res.* 19, 1–10. <http://dx.doi.org/10.1007/s11676-008-0001-z>.
- Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of the flux measurements for density effects due to heat and water vapour transfer. *Q. J. R. Meteorol. Soc.* 106, 85–100.
- Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithm. *Bound. Layer Meteorol.* 99, 127–150.
- Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Achim, G., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. *Agric. For. Meteorol.* 113, 223–243.
- Ykhanbai, H., 2010. Mongolia Forest Outlook Study (Working Paper No. APFSOSII/WP/2009/21). Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific, Bangkok, p. 49.

